New Capabilities in the Hydrologic Modeling System (HEC-HMS) and Geographic Preprocessor (HEC-GeoHMS)

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Abstract

The Hydrologic Modeling System (HEC-HMS) is designed to perform deterministic hydrologic simulation in support of engineering studies. It assists in planning, designing, and operating projects by providing information about current and future runoff from watersheds, with and without water control structures. It is the integration of models for simulating the hydrologic cycle with models for simulating the operation of engineered structures that make the program useful. Until recently, the program lacked the capability to address some types of studies. Changes in the program framework have been made and new features added to make it more flexible, robust, and complete.

The reservoir element included in HEC-HMS is used to represent any lake, detention basin, or reservoir with a storage-outflow relationship. Previous versions required the user to synthesize a composite storage-outflow relationship that included the behavior of all outlets, spillways, etc. The program now allows for the explicit, physical description of each outlet. Transient events such as a dam failure can also be simulated.

The meteorologic model included in HEC-HMS is responsible for processing all of the relevant atmospheric data to produce the boundary conditions at the land-surface. A variety of methods are currently available for processing precipitation data and one method is available for processing evapotranspiration data. A temperature-index snowmelt method has recently been added to simulate a snow pack. When in use, the precipitation data already available is further processed to represent accumulation and melt of snow.

Most hydrologic simulation is performed using a top-down approach by assuming the meteorologic forcing is fixed. In the real world there are bi-directional feedback connections between different parts of the hydrologic cycle. Recent changes in the HEC-HMS framework make it possible to perform bottom-up simulation that can be used to support feedback.

The HEC-HMS framework that manages data and simulations has been made much more flexible and robust. A new interface has been designed to make the most use of the improved framework. The interface is based on the concept of direct manipulation and allows the user to quickly find, view, and modify all of the data objects used in the program.

The geographic preprocessor HEC-GeoHMS has recently been enhanced to better support the development of hydrologic models from digital terrain data. Multiple coordinate systems are now supported. Tools are provided for adjusting the terrain data when it does not produce a drainage network consistent with the observed pattern. It also now provides a number of hydrologic parameter estimation capabilities to reduce the amount of data that must be entered after importing the created models to HEC-HMS.

Introduction

The field of hydrologic simulation has both benefited and suffered from a lack of coordinated research in simulation frameworks. It has benefited from many researchers working to develop a wide range of models that focus on different pathways of the hydrologic cycle. This has led to innovative approaches for solving the problem of linking different portions of the cycle, such as infiltration and surface runoff. Framework development has suffered because the varied development approaches have resulted in models that cannot be easily combined in coordinated software packages.

There are many reasons why models developed by different researchers do not work together. A common problem is short-sighted design where only the immediate problem is solved. The solution is not scalable or expandable for future problems and must often be completely redesigned when a new problem is encountered. A second major obstacle is the movement of data between models. For example, infiltration models must have precipitation data and must pass excess precipitation to a surface runoff model. A third significant challenge is the representation of the same process in different models. A snow process model may include a representation of canopy interception. However, the snow model cannot be easily combined with an infiltration model that also includes a canopy.

HEC-HMS has suffered from many of the problems just described. The program approach is to combine many different models for the pathways of the hydrologic cycle into a single framework. Combining the work of other researches into one software package has shown just how difficult it is to build a tool for addressing a wide range of problems in many different environments. The demand for a software tool that scales from highway overpass design to continental-scale water balance projects has forced the design team to reconsider traditional ideas of program design and development. HEC-HMS is still evolving but is now coming very close to providing a framework suitable for almost any hydrologic simulation project.

Reservoir Simulation

Reservoir simulation in early versions of the program required either a storage-outflow, elevation-storage-outflow, or elevation-area-outflow curve. This required the user to synthesize a curve external to the program that accounted for all outlets including: pipes, spillways, and other methods of releasing water from the reservoir. Outflow was computed with the modified Puls method by assuming one routing step. This approach was very restrictive and limited the type of reservoirs that could be simulated. Real reservoirs often have a variety of spillways, hydropower tunnels, diversion pumps, inlet towers, and many other types of outlets. Especially during the design phase, the engineer needs to be able to quickly evaluate different structural alternatives without reducing the alternative to a storage-outflow curve. For some types of outlets, it may not even be possible to reduce the behavior to a single storage-outflow curve.

The design team began working in late 2001 to expand the reservoir simulation capabilities of the program. Work began by building a solution algorithm for routing flow through the reservoir. The algorithm would initially accommodate an outlet pipe, spillway, dam overflow, and dam break. It was determined that a suitable algorithm would have the following properties:

1. Allow an arbitrary number of reservoir outlets.
2. Expand to include future outlet types with unknown properties.
3. Permit an adaptive time step for resolving rapid changes such as those that occur during a dam breach.
4. Good solution characteristics so that a viable solution can always be found.

Where previous approaches have almost always relied on Runge-Kutta algorithms (Chow *et al.*, 1988), the design team chose to solve the continuity equation directly. The equation is given as:

$$\frac{dS(e)}{dt} - \sum_i Q_i(t) + \sum_j Q_j(e,t) \quad = \quad 0$$

where S is reservoir storage, t is time, e is the water surface elevation in the reservoir, Q_i is the flow for each inflow i, and Q_j is outflow for each outlet j. Within the HEC-HMS framework, all inflows are known for each time step. The outflow is related to reservoir storage through an elevation-storage curve. Brent's method is used to find the root of the continuity equation, which then gives the change in storage and the outflow for the time step (Press *et al.*, 1988). The properties for each outlet and the water surface elevation in the reservoir are used to compute outflow. Properties such as the invert elevation of a spillway determine if there is any outflow for a given water elevation. If the water elevation is above the invert, then outflow for the spillway is computed with the broad-crested spillway equation, for example.

One additional piece of information is provided to each outlet for each iteration of Brent's method during a time step. A stage-rating curve is used to compute the tailwater surface elevation immediately below the reservoir due to total reservoir outflow. For each iteration, this value is provided to all outlets for computing submergence.

The new reservoir routing algorithm based on a direct solution of the continuity equation using Brent's method has all four properties needed for a good algorithm. It dramatically increases the reservoir simulation capabilities of the program by allowing the user to specify outlets instead of a storage-outflow curve. While the current outlets are limited to orifice pipe, broad-crested spillway, ogee spillway, level and non-level dam overflow, and dam break, many other types can and will be added in the future.

Meteorology

Atmospheric conditions provide the boundary condition for almost all surface-water hydrology simulation. Precipitation drives the infiltration and surface runoff. Solar radiation, air and water temperatures, wind speed, humidity, vegetation type and density, and depth of the root zone are factors that drive evapotranspiration (Ponce, 1989; Gupta, 1989). Temperature also determines whether precipitation will fall as rain or snow. Once snow is on the land surface, air temperature, elevation, slope and aspect of the land surface, wind, energy and moisture transfer, and vegetation affect the accumulation and melting of the snow pack (Ponce, 1989).

The meteorologic model in current versions of the program only prepares subbasin-average rainfall and potential evapotranspiration boundary conditions. This is a serious limitation in much of the United States where winter weather almost always includes snowfall. Work has been underway to add a snowmelt component to the meteorologic model. The first snowmelt model is a temperature index method that works with elevation bands or on grid cells. According to Ponce (1989) "an index is a readily measured meteorologic or hydrologic variable that is related to a physical process in need of monitoring and whose variability can be used as a measure of the variability of the physical process."

Using elevation bands, each subbasin is divided into an arbitrary number of units where each unit has a mean elevation and percentage of the subbasin. For example, one band in a subbasin could be defined to include all of the area between 2,000m and 2,200m elevation. The mean elevation would be 2,100m and might occupy 40% of the subbasin. Calculations are then performed once for the band and assumed to represent 40% of the subbasin.

Using grid cells, the subbasin is overlaid with a grid of fixed, rectangular cells. The same calculations are performed as for the elevation band approach except that each grid cell may have unique parameters, including elevation.

The temperature index approach to snowmelt modeling uses the general equation:

$$q = M_R \left(T - T_B\right)$$

where q is the volume of melted snow, M_R is the melt rate in volume per degree Celsius, T is the air temperature in degrees Celsius, and T_B is the base temperature above which snow melts. However, runoff processes for a snow pack are not simple and make the computation of M_R complex.

The approach used in HEC-HMS for computing M_R follows the same approach developed by Daly *et al.* (1999) and also includes cold content and liquid water capacity concepts. Figure 1 shows the basic steps for the snowmelt algorithm. Incoming precipitation may be intercepted in the tree canopy and subsequently evapotranspired. Through-fall is determined to be rain or snow depending on the temperature. Snow adds to the accumulated pack while rain does not. Small precipitation rates are treated as "dry" melt and M_R is computed from a user function of melt rate versus antecedent temperature index (ATI) and modified using an annual pattern.

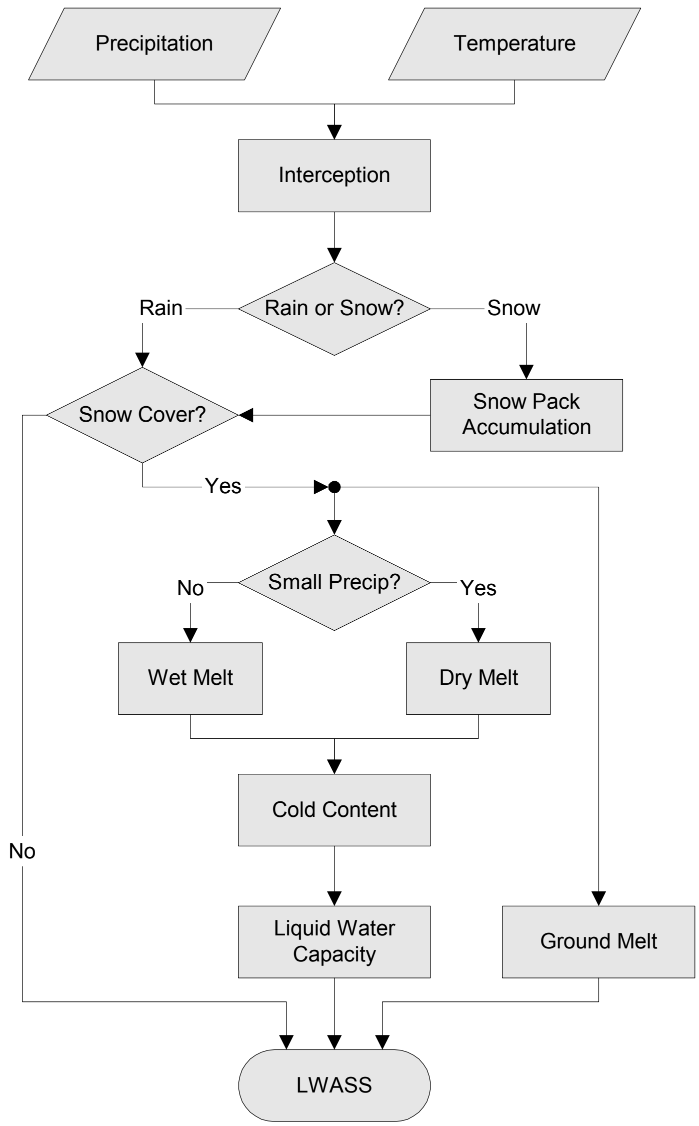

Figure 1. A flowchart of the temperature index snowmelt algorithm recently added to the program and now in testing. Intercepted precipitation can evapotranspire. Temperature is used to determine if precipitation is rain or snow. Small precipitation is defined by the user in mm/hr. Ground melt occurs as long as there is snow cover. Output from the model is liquid water available at the soil surface (LWASS). *After Daly et al. (1999)*

The ATI simulates the ripening of the pack and the tendency of the melt rate to decrease with time as ice crystals in the pack consolidate. Large precipitation rates are treated as "wet" melt and M_R is set to a user-specified value.

The melt volume resulting from the computed melt rate and temperature differential is compared to the cold content. Cold content is analogous to negative energy and refreezes liquid water when the snow pack is cold. Once the cold content has been exhausted, the liquid water holding capacity must be filled before infiltration or surface runoff can begin. In addition to decreasing because of refreezing melt or rain, it can be increased by a separate antecedent temperature index that simulates warming or cooling of the pack by the air. Ground melt occurs whenever a snow pack is present. Liquid water from pack melt, ground melt, or rain on pack-free ground is labeled liquid water available at the soil surface (LWASS) and is available for infiltration into the soil or surface runoff. While this approach introduces complexity to the simple temperature index approach, it results in good simulation results without introducing the complexity and data demands of an energy balance approach (Davis *et al.*, 1999).

The addition of snowmelt to the meteorologic model completes the general framework for computing boundary conditions to the land surface. Other evapotranspiration and snowmelt methods may be added in the future. Nevertheless, the framework for processing time-series data and gridded data is in place. Adding new methods for processing the data to create boundary conditions will be relatively simple.

Feedback Looping

Many pathways in the hydrologic cycle are affected by feedback looping. The best example of feedback is the soil-plant-atmosphere continuum. It is not possible to properly determine the amount of percolation from the soil into the aquifer without also knowing how much water will be transpired by plants. However, it is not possible to determine the amount of transpiration without considering the soil moisture content and the atmospheric conditions. In principle, determining percolation out of the soil column requires an iterative approach that considers atmospheric conditions and plant transpiration as well.

Most hydrologic models do not use feedback looping and instead use a top-down simulation approach. In this approach, the atmospheric boundary conditions on the land surface are computed first. Boundary conditions considered might include precipitation, potential evaporation and transpiration, snowmelt, and wind speed. Next the actual transpiration is computed from the potential amount and the available soil water content. Next the infiltration and percolation calculations are performed. Finally, the surface runoff and then baseflow calculations are performed. Users of these types of models often argue that feedback can be ignored or that a sufficiently small time step is a good approximation.

Previous versions of HEC-HMS have approached modeling using the top-down approach. Changes are now underway to convert the process to a bottom-up approach that will allow feedback. Using object-oriented design concepts, the computations are initiated by attempting to compute total subbasin outflow. That in turn requires the percolation and surface runoff to be computed. Those processes also require other results to be computed. At each stage there is the opportunity to compare newly computed results to results from a prior iteration. This allows for the full consideration of feedback looping with only minor adjustments to the organization of the program. It also does not require any structural changes to existing models included in the program that are not intended to include feedback.

Interface Design

The usability of simulation software is determined almost entirely by the design of the interface. Ten years ago, programs were differentiated as having interfaces or graphical interfaces. A so-called "interface" implied a command line control for the program whereas a "graphical interface" used a mouse. Today that distinction is irrelevant because all software is assumed to have what was previously called a graphical interface. However, the use of graphical methods for interfacing with the user does not imply usability.

A good program interface can only be judged in the context of how well it does what it is designed to do. Regardless of the tasks a program performs, it should have the following properties (Cooper, 1995):

1. Assist the user in looking smart.
2. Prevent the user from making mistakes.
3. Facilitate completion of appropriate volumes of work.
4. Provide an enjoyable work experience.

A critical evaluation of previous HEC-HMS versions was completed by the design team and a number of areas for improvement were identified. The entire interface was abandoned and a new one is being constructed as a replacement. In addition to adopting industry standards for technical software, it implements the four properties proposed by Cooper. Standard templates are provided for formatting results in the manner generally used by professional hydraulic engineers so the user looks smart. High-level features are disabled until the required low-level components have been created, thus preventing many common mistakes.

A new "watershed explorer" (Figure 2) centralizes all components of a project, making it faster to find and use data components. New background maps like aerial photographs and new graphing capabilities make it more fun to review data and results.

The watershed explorer is the biggest part of making the program more usable. Previous versions used several different screens, each with lists of data objects, for organizing all of the different types of data used in hydrologic simulation. The explorer organizes all of the input data in one location. It locates all of the computation tools in a second location. Finally, it makes all computed results available in a concise third location, which is an advantage over current versions that only allow results from one simulation run to be available. The natural progression from data, to simulation, to results also helps the user stay organized. As an added benefit, by consolidating the many types of data with the watershed explorer, the program is also easier for new users to learn.

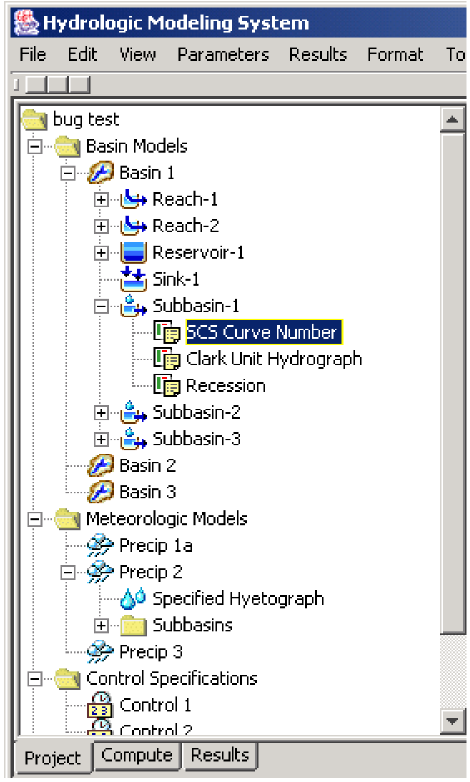

Figure 2. The first tab of the new Watershed Explorer showing the organization of some of the many types of data used by the program. Simulation runs are organized on the second tab and simulation results are available on the third tab.

Geospatial Support with HEC-GeoHMS

The geographic preprocessor HEC-GeoHMS analyzes geospatial data to assist in formulating and building an HMS model. GeoHMS analyzes digital terrain data automatically delineating watershed boundaries and drainage networks. Other tools in GeoHMS allow for revision to watershed boundaries, extraction of basin and stream physical characteristics, and generation of input files for lumped and distributed modeling. Through a Cooperative Research and Development Agreement (CRADA) with the Environmental Systems Research Institute, Inc. (ESRI), recent enhancements in GeoHMS include multiple coordinate systems support, digital terrain smoothing, and estimation of hydrologic parameters.

The coordinate system and map projection of the digital terrain data often become an important issue because of the amount of distortion in direction, distance, area, and shape. The ability to minimize these map distortions is very desirable when it comes to extracting physical characteristics of the basins and streams, such as basin area and stream routing reach length. Therefore, GeoHMS now supports the main coordinate systems and projections, including Albers-Equal Area, Universal Transverse Mercator (UTM), Tranverse Mercator, Lambert, and the State Plane Coordinate System. Users can specify the coordinate system for the digital terrain data that has the least distortion for their study area. The extraction of physical characteristics will be based on the user-specified coordinate system. When using the ModClark distributed modeling approach as depicted in Figure 3, GeoHMS will re-project the subbasin delineation from the user-specified coordinate system to that of the precipitation data. A grid-based subbasin representation that is compatible with the grid-based precipitation will be constructed with options to include gridded curve number loss rates and gridded snowmelt.

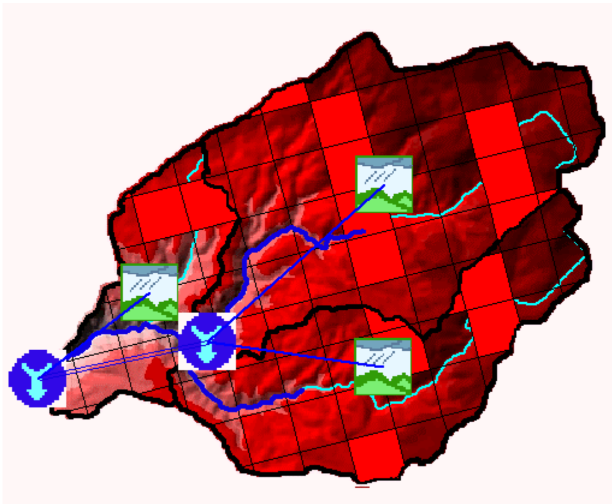

Figure 3. ModClark grid-based subbasin representation.

Tools are provided in GeoHMS for adjusting the terrain data when it does not produce a drainage network consistent with other maps and field conditions. Many users in the past have used the simple “burning in” techniques to force a stream network on the digital terrain. This simple “burning in” technique allows the user to abruptly lower only the stream cell elevation by a fixed amount. Similar to the simple “burning in” technique, a new Terrain Reconditioning method is being implemented in GeoHMS to allow the user to lower the elevation of the stream cell and also provides an option to gradually lower the neighboring cells along the stream. This method creates a gradual transition from the overbank to the stream centerline. In many cases where the stream cells in the digital terrain and the stream vector line are not aligned, this method can eliminate the undesirable side effects of fictitious islands near the stream centerline and parallel streams. These side effects are often encountered when the simple “burning-in” technique is used.

In addition to the terrain reconditioning techniques, a separate and more comprehensive software package, Digital Dozer, will be available in fall 2003 to assemble digital terrain data from many different data sources and technologies. The Digital Dozer will provide more interactive tools for editing and fixing the digital terrain. Recognizing the need to combine and edit these data into one coherent and representative digital terrain model for the watershed, GeoHMS will provide support and an interface with the newly created Digital Dozer software package.

Accurate digital terrain data not only provide a good basis for subbasin and stream delineation, they are essential to estimate many hydrologic parameters which are often based on extracted topographic characteristics as shown in Figure 4. Infiltration loss rates in terms

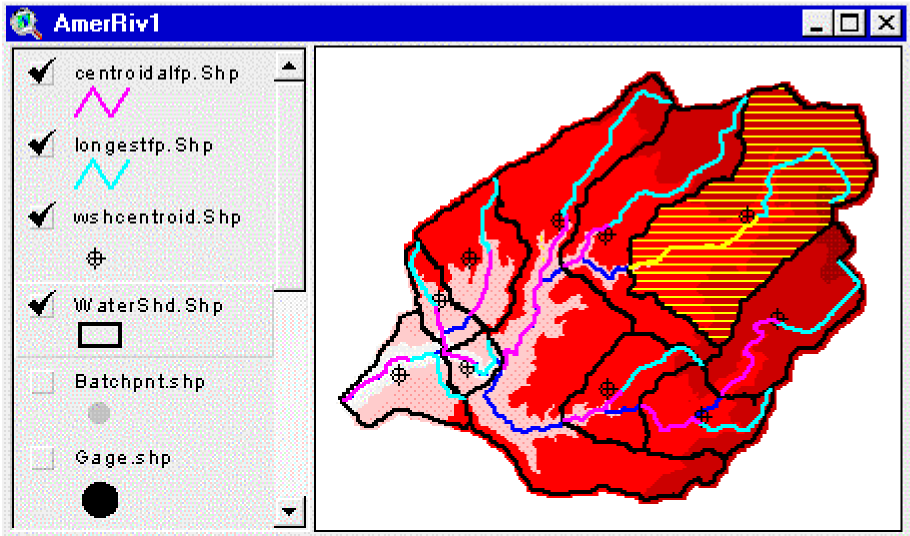

Figure 4. Subbasin and stream topographic characteristics.

of curve numbers can be estimated as lumped and grid-based quantities that are based on soil and landuse databases. Time of concentration for each subbasin is estimated in accordance to the Natural Resources Conservation Service TR-55 methodology, where the longest flow path is divided into sheet flow, shallow concentrated flow, and channel flow. A spreadsheet template is linked to GeoHMS and accepts GIS extracted topographic data and user-specified input to compute the time of concentration. GeoHMS also facilitates input of field survey data for the Muskingum-Cunge prizmatic shaped channel routing.

Future versions of GeoHMS will incorporate more hydrologic parameters and compute more comprehensive watershed and river characteristics and statistics. Also, GeoHMS will be closely linked with the HEC Data Storage System (HEC-DSS) and its grid processing with the GridUtil program to visualize hydrographs at gages and grid-based precipitation. Users will be able to track both the spatial and temporal variation of precipitation as shown in Figure 5. To make this possible, GeoHMS will utilize the ArcGIS platform with the ArcHydro Data Model.

Conclusions

HEC-HMS is currently undergoing a number of structural changes that expand its simulation capability. A new reservoir algorithm allows the user to directly enter the physical properties of each outlet from the reservoir. The algorithm is expandable and may include a wide variety of outlet types not yet conceived. The meteorologic model now includes components for precipitation, potential evapotranspiration, and snow accumulation and melt. Finally, changes are also under development that will allow it to simulate feedback processes in the soil-plant-atmosphere continuum. These adjustments and enhancements to the simulation framework dramatically increase the types of applications the program can address.

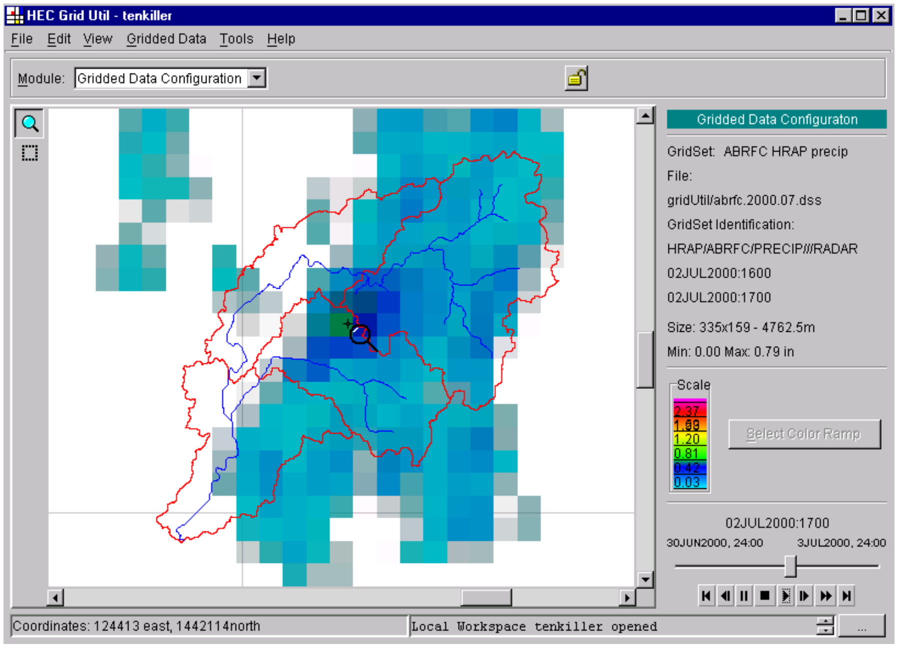

Figure 5. Grid-based precipitation in HEC-GridUtil.

A new interface is also being constructed that improves usability of the program. The new interface includes standard templates for producing formatted results in standard formats. It selectively blocks portions of the program from use until prerequisite components have been created. It streamlines processes to make the program faster to use. Finally, it provides new visualization tools to make it more fun to use. The combination of the new features will provide new levels of benefit to users.

GeoHMS has been recently enhanced for developing hydrologic models from digital terrain data. GeoHMS now supports main coordinate systems and projections for developing hydrologic models. A new terrain reconditioning method has been added for producing drainage networks consistent with other maps and field conditions. Capabilities have also been added to estimate HMS parameters from digital terrain data.

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